Assessment of the quality of fused products

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ABSTRACT: Our work deals with the synthesis of multispectral images at a better spatial resolution by the means of another image having such a resolution. We show the lack of standard procedure to assess the expected benefits of fused products. We discuss the case of the reference that is missing in most cases. We discuss the principles of the assessment protocol. One principle is that the constructed synthetic images should be close to reality. The second principle is that the fused products should offer a strong consistency with the original data set. This results into two properties of the fused products. We propose a protocol that assesses the quality of fused products with respect to these properties. We define a general framework and the protocol is still open.

1 INTRODUCTION

A large number of Earth observing systems offer multispectral images and panchromatic images having different spatial resolutions (Table 1). The benefits of having multispectral images with a higher spatial resolution have been described in several studies. On the one hand, the high spatial resolution is necessary for an accurate description of the shapes, features and structures. On the other hand, depending on the application and the level of land cover complexity, the different types of land-use are better classified if high spectral resolution images are used. Hence, there is a desire to combine the high spatial and the high spectral resolutions with the aim of obtaining the most complete and accurate (in terms of spectral band) description of the observed area.

This can be performed by sensor fusion approaches. Such methods apply on a data set comprising multispectral images B_{il} at a low spatial resolution *l* and images A_h at a higher spatial resolution *h* but with a lower spectral content (Table 1). These methods aim at constructing synthetic multispectral images B^*_{ih} having the highest spatial resolution available within the data set (e.g. the four bands B at 5 m or 2.5 m in the case of SPOT-5) which are close to reality by performing a high-quality transformation of the multispectral content when increasing the spatial resolution.

Such fusion operations are called synthesis of images. Starting from an ensemble of images having different resolutions, they aim at producing fused products that have the best of the spectral resolution and the best of the spatial resolution. In this paper, we are limiting ourselves to the case where the aim is to produce fused products that are similar to what would be observed by a multispectral sensor, if it were having this high resolution *h*.

A large number of methods exist (Pohl and Van Genderen, 1998). Commercial softwares propose numerous methods and it is not obvious for non-specialists to select one method or another for a given case. Vendors of satellite images are also proposing fused products. Value-added companies purchase original satellite images and produce themselves fused products. These producers (whether they are original vendors or not) may hesitate to select one of these methods; they often use methods, which are not the most suitable for their customers. The customers face a similar problem: they have no easy mean to choose between a fused product or a method.

Table 1. Examples of Earth observing systems offering various modalities at different spatial resolution

Satellite	Low spatial (*l*) and high spectral resolutions Spectral band (µm) – resolution (m)	High spatial (*h*) and low spectral resolutions Spectral band (µm) – resolution (m)
SPOT-4	B1 – [0.50, 0.69] – green – 20 B3 – [0.78, 0.89] – red – 20 B4 – [1.58, 1.75] – NIR – 20	B2 – [0.61, 0.68] – yellow – 10
SPOT-5	B1 – [0.50, 0.59] – green – 10 B2 – [0.61, 0.68] – yellow – 10 B3 – [0.78, 0.89] – red – 10 B4 – [1.58, 1.75] – NIR – 20	P – [0.48, 0.71] – 5 or 2.5
Ikonos	[0.45, 0.53] – blue – 4 [0.52, 0.61] – green – 4 [0.64, 0.72] – red – 4 [0.77, 0.88] – NIR – 4	P – [0.45, 0.90] – 1
Quikbird	[0.45, 0.52] – blue - 2.8 [0.52, 0.60] – green - 2.8 [0.63, 0.69] – red - 2.8 [0.76, 0.90] – NIR - 2.8	P – [0.45, 0.90] – 0.7

2 THE NEED FOR A NORMATIVE FRAMEWORK

Several comparisons between methods have been published and are regularly published. However, results of these comparisons poorly disseminate in the community and there is lack of knowledge among producers regarding these methods, their advantages and limits. Above all, the lack of standardization of protocols for comparison is a strong limitation to the dissemination of knowledge. There is a **need for a normative frame of work**; there is no commonly-adopted procedure or even criteria to assess the expected benefits of a method or a fused product. The survey of literature shows a real poverty in that respect. Some efforts have been made recently (Wald *et al.* 1997) but a lot still remain.

In addition, one should note that quality assessment relies on several important factors:

- the type of landscapes is decisive. Using the same algorithm, fusion of images covering urban areas exhibiting a lot of spatial details will not deliver the same results than images having the same spatial resolution but covering ocean or large forest areas. The latter usually show less spatial details and thus the fusion process should perform better;
- the resolution is a key factor. Let take an example. Urban zones at resolutions of 80 or 40 meters may not show tremendous differences. Wald, Ranchin (1995) found that the loss in information (expressed as the variance) over the inner city of Barcelona (Spain) when passing from a resolution of 40 to 80 m was approximately 20 %. Consequently, a fusion process is expected to perform efficiently. However, at better resolutions of 10 m or better, the situation is dramatically different: the images will show a lot of details (high frequencies) and the fusion process will encounter more difficulties to be as efficient.

These factors have their own incidence on the resulting quality. Consequently, it is difficult to assess *a priori* the quality of an algorithm. It is easier as well as more appropriate to position ourselves at the end of the fusion process, and assess the quality of the fused product (*a posteriori*), independently from the applied fusion method.

This communication intends to pave the way for the standardization of quality assessment of fused products. A normalized protocol would contribute to a better acceptation and use of fused products by customers and thus will have a strong impact on industry. Such a protocol and the associated quantification of the quality may help in

- system requirements by providing a framework for users to better specify their needs for information;
- information communication by allowing producers, customers and other persons from all backgrounds to communicate the usefulness of an image to perform a task;
- and analysis by providing an instrument, or part of it, for developing other system performance tools or for assessing the effects of changes in the fusion methods or sensor design or image chain or production line on image quality.

3 QUALITY ASSESSMENT NEEDS A REFERENCE

Quality assessment implies a comparison between the fused product, its properties or some derived quantities, and a reference. A good quality is obtained if the product is close to this reference. The major problem here is the selection of the reference. If it does not already exist, it should be constructed. Then, the comparison may be performed using qualitative (e.g. visual analysis) and quantitative criteria.

The problem of selecting a reference is not new and has been reported by several authors. In some specific cases, authors were only interested in testing fusion methods. Consequently, some used the original images A_h and B_{ih} as references and degraded their resolution by a factor, say 2, to create pseudo-acquired images B_{il}. The fusion process is then applied on these pseudo-acquired images (Munechika *et al.* 1993). When A_h is not available, others constructed the A_h set by a combination of images B_{ih} prior to the spatial degradation leading to B_{il} (Aiazzi *et al.* 2002; Boissezon et Laporterie 2002); this offers also the advantage of removing the problem of geometric alignment that is often plagging quality in fusion process (Blanc *et al.* 1998). In these cases, the reference is available and corresponds to the original images B_{ih}.

However, in most cases, the reference B_{ih} is not available and must be constructed.

3.1 *Resampled Image Or Statistical Quantities As Reference*

One of the most common approaches found in literature consists in resampling low resolution images B_{il} up to the high resolution h: $B^{interp}{}_{ih}$, and assuming that these images constitute the reference (Alparone *et al*. 1998; Chavez *et al.* 1991; Liu 2000; Terretaz 1998; Yocky 1996). In any case, the interpolated images are not representative of what would be observed by a similar sensor with a higher resolution, and these interpolated images cannot constitute a valid reference. It follows that this approach is not valid and should not be used. It is in itself a paradox: if interpolated images are assumed to be the reference, why should one bother with fusion methods?

Other protocols try to avoid establishing images of reference, mostly by using some statistical quantities or features derived from the original data set and from the fused products. One example is the use of the histograms (Garguet-Duport *et al.* 1996). The principle behind is that the histograms of the original B_{il} and the fused product B^*_{ih} should be similar. The comparison of histograms is a fairly good estimator of image quality, and is easy to handle. However, the effect of change in spatial resolution on histograms and on any statistical quantities should not be neglected. It is known that spatial averaging has a tendency to clip the aisles of the histogram. Consequently, a fused product B^*_{ih} will likely present a larger signal dynamic than the original image B_{il}. Table 2 illustrates the change in statistical quantities with spatial resolution. We computed the mean and variance of a panchromatic image acquired by the satellite Quickbird over a city at the original resolution and a degraded one. One may notes that if the mean value remains the same at resolution $h=0.7$ m and $l=5.6$ m, the variance decreases by a factor 2! This observation is similar to that already reported above about the city of Barcelona in section 2. Accordingly, there is a huge discrepancy between the statistical quantities of B_{il} and B^*_{ih} and it is not valid to compare them for assessing the quality of B^*_{ih}.

Table 2. Change of statistical quantities with spatial resolution. Panchromatic image of the city of Strasbourg (France). Units are gray values (11 bits).

	Resolution h = 0,7 m	Resolution l = 5,6 m
Mean	249	249
Variance	$2.84\ 10^4$	$1.52\ 10^4$

This non-preservation depends upon the observed type of landscape. The more energetic the high frequencies (i.e., the small size features) at scale h, the more dissimilar the statistical distributions at scales h and l. This observation has been reported by several authors in various domains (Lillesand, Kiefer 1994; Wald *et al.* 1997; Woodcock, Strahler 1987) and has been explained theoretically in some cases by Raffy (1993). That means that we should not try to identify the statistical properties of a fused product to those of the original image: histogram, cumulative frequencies, variance, entropy, correlation coefficient... Therefore, any protocol for quality assessment based upon the comparison of statistical quantities is not valid and should not be used.

3.2 *The High Spatial – Low Spectral Image As Reference*

Zhou (1998) considers that the high frequencies of the fused product B^*_{ih} should resemble the high frequencies of the high resolution image A_h. Though both images have the same spatial resolution h, contrary to the previous approaches, the principle is highly questionable.

The expected similarity implies that the authors assume that there is no change in high frequencies with spectral range. This is contrary to observations. For example, anyone may notes that bottom features that are visible under shallow waters in blue range and broadband range (panchromatic), and are not visible at all in near-infrared range. The authors themselves (Li, 2000) feel uneasy about their approach but do not discuss their contradiction: they argue that the correlation coefficient between these high frequencies images should be high for a best quality but should not be too high! Accordingly, this approach should not be used.

3.3 *Proposal For A Reference And Limitations*

The reference should significantly represent the reality. Considering that the only valid reference is made of the original images B_{il}, we propose to call upon a change in scales and to operate at a lower resolution, an approach promoted by Munechika et *al*. (1993), Mangolini (1994) or Wald et *al*. (1997):

- two sets of images A_l and B_{iv} are created by downsampling A_h and B_{il}, to respectively the low resolution l (A_l) and the very low resolution v (B_{iv}) with $v = (l^2/h)$;
- the fusion method is applied twice, firstly to the set (A_h, B_{il}) and then to (A_l, B_{iv}), resulting into two sets of fused images B^*_{ih} at resolution h and B^*_{il} at resolution l;
- the original images B_{il} serve as references. A comparison is performed between B_{il} and B^*_{il} by the means of visual and quantitative examinations and analysis of the similarities and discrepancies;
- finally, the quality observed for the fused products B^*_{il} is assumed to be close to the quality that would be observed if a reference at resolution h were present.

Such an approach is easy to implement and alleviates the lack of "true" images B_{ih}. This raises a question. How can the assessment of quality of the synthetic images be made at the highest resolution h based upon the one carried out at the lowest resolution l? In other words, how can one extrapolate the quality assessment made at the lowest resolution to the highest resolution?

Intuitively, one thinks that, except for objects having a size much larger than the resolution, the error should increase with the resolution, since the complexity of a scene usually increases as the resolution is getting better and better. That is, one may expect the error made in B^*_{il} at the highest resolution h to be greater than in B^*_{il} at the lowest resolution l. This should be particularly the case if the high frequencies to be injected at resolution h in the multispectral image B_{il} are very energetic.

This question is relevant to the influence of the spatial resolution on the quantification of parameters extracted from satellite imagery that has been already discussed above. The published studies demonstrate that the quality of the assessment of a parameter is an unpredictable function of the resolution. It is a very complex function of the power of the high frequencies relative to that of the very high frequencies, *i.e.* objects that are unresolved at the resolution h, and of the distribution of these unresolved objects within the pixel. The multispectral aspect adds dramatically to this complexity.

It follows that the quality of the synthetic images at the highest resolution h cannot be predicted from the assessments made with synthetic images at the lowest resolution l. Practically, we may rely on the results of several assessments published or performed at Ecole des Mines de Paris. They show that there is no clear relationship between the quality parameters obtained for the fused products B^*_{ih} and B^*_{il}, or between B^*_{il} and B^*_{iv}, as expected. Nevertheless, it has been often found that the quality was best or similar at the resolution h (respectively l) relative to the resolution l (respectively v). It does not prove that estimates should be better at the resolution h than at the resolution l. However, it seems reasonable to assume that the quality of the synthetic images at the highest resolution h is close to that at the lowest resolution l.

Practically, the downsampling should be performed in such a way that it simulates what would be observed by a lower resolution sensor. Many authors use an averaging operator on a window of 3 by 3 pixels or more. Such an operator is not appropriate here since it does not have the ability to separate scales correctly, that is, to separate structures of small size from larger ones. Other filtering operators should be used, some of them simulating a given modulation transfer function (MTF) of a sensor. Thierry Ranchin (personal communication) performed a comparison of some operators on a few scenes, such as a sine cardinal (sinc) kernel truncated by a Hanning apodisation function of size 13 by 13 pixels, a truncated Shannon function, a bi-cubic spline, a pyramid-shaped weighted average, and the wavelet transforms of Daubechies (regularity of 2, 10 and 20). It showed relative discrepancies between the results on the order of a very few per cent. In conclusion, there is an influence of the filtering operator upon the results, but it can be kept very small provided the operator is appropriate enough. A bi-cubic spline offers often a good trade-off.

4 PROPOSAL FOR A PROTOCOL

Our aim is to propose a framework, wide enough to deal with most cases. A protocol is an ensemble of rules and procedures that should be followed by the fusion community to comply with standard assessment. We believe that the protocol should focus on the objective of fusion : fusion methods must aim at constructing synthetic images B^*_h, which are close to reality. The challenge is to establish a set of practical rules and criteria that on the one hand, are recognized by the community as necessary and sufficient to assess the quality and on the other hand, are easy enough to be accepted, implemented and used by the professionals.

Published works deal with various properties of the fused products. Some focus on the spatial properties, using PSF-like functions (Li 2000), high-pass filters (Zhou 1998) or visual analyses (IRARS 1996). Others deal with radiometric properties, computing bias and root-mean square differences (RMSD) (Alparone *et al.* 1998; Wald *et al.* 1997). Multispectral properties are of concern in most of these works, either in the form of visual analysis of color composites (Boissezon, Laporterie 2002; IRARS 1995; Vrabel 2000) or by the means of quantitative criteria (Aiazzi *et al.* 2003; Wald *et al.* 1997).

4.1 *The Two Properties of the Fused Products To Check*

Our protocol should therefore consider the mono-modality (spectral band) and the multi-modality (multispectral) aspects. In the mono-modality aspect, one considers each modality separately. Each fused modality is compared to the corresponding reference and the assessment is performed without considering the other modalities. Quantities are computed for each modality. It may be possible to arrange these quantities into an integrated one, e.g. sum of the individual RMSD (Munechika *et al.* 1993) or ERGAS (Wald 2002) in order to get a global idea of quality. In the multi-modality aspect, one considers the ensemble of the modalities and assesses whether its multi-modality properties are close to those of the reference ensemble. Thus, we propose that the protocol should check both aspects. For the sake of simplicity, we propose to check them separately, that is to assess firstly the mono-modality aspect and then the multi-modality aspect.

In the domain under concern, it is also very important that the fused products offer a strong consistency with the original data set. This means that if the fused product is spatially degraded down to the original low resolution l, it should coincide with the original low-resolution data set B_l. This should be true for each modality as well as for the multi-modality set. This fused product property may appear as trivial. However, several well-known methods such as IHS produce fused products that offer very low consistency with the original data set. Accordingly, we propose to test this property.

Thus, our protocol should establish rules and criteria to check two properties, that themselves comprise two aspects: mono- and multi-modality.

4.1.1 *The consistency property*

Any synthetic image B^*_h once degraded to its original resolution l, should be as identical as possible to the original image B_l. This should be checked for individual modality B_{il} as well as for the multi-modality set.

For individual modality, the equation can be written as:

$$D_1(B_{il}, (B^*_{ih})_l) < \varepsilon 1_i \qquad (1)$$

where $(B^*_{ih})_l$ denotes the image B^*_{ih} resampled at resolution l and D_1 is a distance between B_{il} and $(B^*_{ih})_l$. Approximation induced by the resampling of B^*_{ih} into $(B^*_{ih})_l$ should be taken into account: the limit $\varepsilon 1_i$ is determined by the requested degree of accuracy. $\varepsilon 1_i$ should be small for each modality. An instance of D_1 is the square root of the mean of the squared differences $(B_{il} - (B^*_{ih})_l)$ on a pixel basis. A typical value for $\varepsilon 1_i$ is 0.05 times the mean value of B_{il}. Depending upon the objectives, other distances may be used in order to enhance specific properties in the image, e.g., structures or shapes. Actually, several distances are to be used concomitantly and D_1 may be considered as an ensemble of distances.

For the multi-modality aspect, the equation can be written as:

$$D_2(B_l, (B^*_h)_l) < \varepsilon 2 \qquad (2)$$

where D_2 is a distance between the sets B_l and $(B^*_h)_l$. As previously, approximation induced by the resampling of B^*_h should be taken into account. $\varepsilon 2$ should be small for all modalities; this ensures the similarity between the sets B_l and $(B^*_h)_l$. An instance of D_2 is the difference in the frequencies of the most frequent spectra, which are those influencing the most the classification process coming next (Wald *et al.* 1997), or the spectral information divergence (Aiazzi *et al.* 2003). Depending upon the objectives, other distances may be used in order to enhance specific properties in the image, e.g., structures or shapes. Several distances may be used concomitantly and D_2 may be considered as an ensemble of distances.

Note that this consistency property is similar for the mono-modality aspect to the first property proposed by Wald *et al.* (1997) and to the first property of Li (2000).

4.1.2 *The synthesis property*

Any synthetic image B^*_h should be as identical as possible to the image B_h that the corresponding sensor would observe with the highest spatial resolution h, if existent. This should be checked for individual modality B_{ih} as well as for the multi-modality set.

For individual modality, the equation can be written as:

$$D_3(B_{ih}, B^*_{ih}) < \varepsilon 3_i \qquad (3)$$

where D_3 is a distance between B_{ih} and B^*_{ih} for the modality i. The ensemble D_3 of distances may be the same than D_1 or different depending upon the objectives. This property applies to each modality taken separately; it does not imply an accurate synthesis of the multi-modality characteristics of the set *B* when increasing the spatial resolution. This should be an additional equation:

$$D_4(B_h, B^*_h) < \varepsilon 4 \qquad (4)$$

where D_4 is the distance between the sets B_h and B^*_h. The ensemble D_4 of distances may be the same than D_2 or different depending upon the objectives.

Note that this synthesis property is similar to the second and third properties proposed by Wald *et al.* (1997) and for the multispectral aspect to the third property of Li (2000).

4.2 *The Protocol*

Using these properties and our proposal for a reference, we may establish a protocol for the quality assessment. The protocol comprises five operations.

First Operation. Perform the fusion process on the data sets A_h and B_l. We obtain a set B^*_h.

Second Operation. Resample the set B^*_h down to resolution *l*. Check the consistency property by comparing B_l and $(B^*_{ih})_l$.

Third Operation. Resample the data sets A_h and B_l down to respectively A_l and B_v. Perform the fusion process on these new data sets. We obtain a set B^*_l.

Fourth Operation. Check the synthesis property by comparing B_l and B^*_l.

Fifth Operation. Assuming that the synthesis quality assessed with B^*_l is equivalent to that of B^*_h, completes the quality assessment.

5 CONCLUSION

The proposed protocol permits to assess the quality of any fused product, provided the aim of the user is to handle synthetic images of higher spatial resolution *h* that are as identical as possible to the images B_h that the corresponding sensor would observe with the highest spatial resolution *h*, if existent.

This protocol has been made possible by the construction of a reference and the assumption that increasing the resolution from *l* to *h* does not change too much the quality assessed at resolution *l*, starting from resolution *v*. This is likely the major limitation of our proposal; this point cannot be demonstrated theoretically. Performing more experiments might support this assumption.

Moreover, the proposed protocol is generic because it is able to handle any kind of images, not depending on the ratio or the fusion method used.

Thus, it is presently a framework and is still open. The distances in Equations (1-4) are to be defined as well as the criteria defining the quality, which are the detailed expressions of Eqs 1 to 4. Some examples have been given, others can be found in the literature. It is likely that these distances depend of the final objectives of the users (Ranchin, Wald 2003). However, one may expect several distances and criteria to be significant enough in all cases to be adopted as standards, such as bias or difference in variance. In conjunction with quantitative analysis of the differences between fused products and references, the literature and experts recommend also to perform a visual analysis of these same data sets and the differences.

These distances and criteria are discussed in this session on data fusion with new proposals compared to literature.

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